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Editorial

Editorial: Networks Applied in Science Education Research

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Science education research is, in many ways, involved with exploring relational aspects of diverse elements that affect students' learning outcomes; at one end, the elements may be concepts to be learned, and at the other end, the relations between students in different types of learning settings and environments and, ultimately, how such elements may interact. The learning situations and how they affect the learning outcomes can be considered as a complex system, with many types of interacting elements and their relations. For such situations, complex network methods provide approaches, which are suitable for describing and understanding, how the plentitude of factors involved in learning are connected and, together, affect the learning outcomes.

In recent years, complex network approaches have gradually found their way also in science education research. For example, they have been applied for example in exploring: how students understand scientific concepts and conceptual systems [1–7], how teachers see relationships between relevant subject knowledge and pedagogical content knowledge [8], how students conceive the history of science [9,10] or the nature of science [11]. In addition, the network approaches have been applied in examining how sociodynamics affect learning situations [12–15] and how networks can be used in assessment [16,17]. In all these studies, the focus is in finding relationships between the basic elements—concepts, attitudes, sentiments etc.—which are seen to be relevant for the topic to be learned. The advantage of complex networks becomes evident in situations, where it reveals new and complex constellations of factors that co-occur and affect the structure or dynamics of the system.

Until now, science education research, however, have been relatively slow to adopt the complex networks as a research tool. This is somewhat surprising, given the fact that many research fields, which are relevant for science education research, have found the complex networks as a useful research approach. The complex networks have found applications in diverse areas, ranging from information and communication systems to cognitive systems and sociological, political and economic systems. In all these diverse cases, the basic idea has been to treat the systems of connected, interacting set of elements, where the focus is on relationships between the elements and how these relationships affect the behavior of the system (see e.g., refs. [18,19] and references therein). The educational problems are clearly a field of research, where similar kinds of approaches may turn out to provide valuable insights and new ways of conceptualization.

If we acknowledge the notion that phenomena related to learning are complicated and complex, we should approach them as genuine complex systems. To advance science education research in that direction, we need to develop research tools, which are flexible in providing comprehensive, integrative picture of the complex phenomena one encounters in science education. Furthermore, the method should be explicit about the type of elements and entities it deals with, and how the elements and entities are involved in the phenomena of interest. To fulfill such requirements, complex networks provide promising approach, with the prospect of similar kinds of advances as found in close research fields, like cognitive science, learning psychology and social dynamics.

From the methodological point of view, complex network-based methods are essential for analyzing and modelling effects and dependencies, which are indirect or mediated between the entities or elements that are involved in the target phenomena. As pointed out by Zweig, in her monograph "Network Literacy" [18], it is the indirect and mediated effects where we really need networks and network based methods, while all the direct effects contained in the relations can be modelled and analyzed by traditional statistical methods (although the networks may helpful in visualizing the dependencies). Another good reason in addition to indirect effects, is the exploration of the dynamics of the systems. These both kinds of situations are illustrated in this Special Issue. The issue contains 13 examples, varying from studies focusing on concept learning and conceptual understanding in different contexts of learning, to the social dynamics and sociosemantics of learning. These studies provide a state-of-art picture of how different ways networks and network methods can be used in providing deeper understanding of learning processes, how the processes are related and how they affect learning outcomes.

While networks are often utilized for visualizations, infographics and providing insights on relational dependencies, the true power of networks derives from the possibility to quantify the indirect effects and dependencies, to provide a metrics for dependencies. This, however, brings in a certain degree of mathematical technicalities, which cannot be entirely avoided, and needs to be accepted as a means of gaining new information, not available in other ways. In the studies contained in this Special Issue, this tendency to mathematization for quantification is clearly visible and, as such, it may at first appear even alien to more traditional ways of doing science education research. However, such mathematization is the essence of networks-based methods. It would be tempting to see and apply networks as easy and nice visualizations of important dependencies contained in the empirical data, possibly augmented with concise verbal descriptions of the meaning of connections interpreted from visualizations. Different visualizations highlight different dependencies, and such a multifaceted potential of visual representations is useful for explorative analysis, but also easily tempts oversimplified interpretations. Similarly, the use of suggestive verbal descriptions of the measured quantities (like, e.g., clustering, closeness or betweenness centrality) too easily lead to oversimplifying the meaning of such quantities, which are essentially mathematical quantities related to metrics and topology of the networks (see e.g., [18], especially chapter "Beware of verbal Descriptions—Why Mathematical Equations are Necessary"). This is to remind us that, when network methods are used, researchers should pay attention on proper mathematical description of the quantities they use.

To understand what new views and vantage points complex networks can provide for science education research, we need to ask what kinds of new ways of conceptualization and explanations the networks will provide. The collection of 13 articles in this Special Issue opens up several possible views on those questions, and the studies provide examples how networks may help in constructing the desired integrative view, which can capture the many-faceted relationships present in learning—cognitive and sociodynamical—better than traditional methods.

In the commentary "Applications of Network Science to Education Research: Quantifying Knowledge and the Development of Expertise through Network Analysis", Siew discusses the question, what kinds of cognitive processes and structures are involved in learning conceptual knowledge: what is important, meaningful and useful and what leads to expertise in the given knowledge domain. The study points out also the importance of defining the notion of knowledge so that it yields to analysis. The author has chosen to approach knowledge from a perspective, which can be called relational, in the sense that it conceives knowledge composed of identifiable knowledge items (concepts) and the relationships between these items. The way the problem of learning is outlined and framed in the commentary is a good example of how networks provide new viewpoints on the phenomena of learning and education. Siew's commentary directs attention to generic complex network models, which can be used to understand the complexity of learning and structures involved in it. The importance of such models is that they are also able to generate hypothesis to be tested, is one advantage of network-based approach. This reminds us that the value of networks is not only in empirically driven attempts to provide visualizations and representations of data, but also to provide hypothesis driven approach to test theory-based generic models.

The concept learning, conceptualization and conceptual change are in focus in six articles out of the total 13 in this Special Issue.

In their study, "Investigating Network Coherence to Assess Students' Conceptual Understanding of Energy", Podschuweit and Bernholt steer attention to coherence of energy-related concepts. The vantage point adopted by this study emphasize the context dependence of such general and abstract concepts as energy. The study asks not only if the conceptions are coherent or not, but also if they, as a system, behave coherently in changing situations. To observe and analyze such a dynamic coherence, the study makes use of the complex networks and complex network measures in characterizing coherence. The measures for coherence are then compared with multiple-choice test results to see if there is correlation between them. From a network perspective, the study exemplifies how relevant network measures can be chosen for specific purposes, carefully considering what the targeted phenomenon is.

The concept of energy is also in focus in the article "Transferring Knowledge in a Knowledge-in-Use Task—Investigating the Role of Knowledge Organization" by Kubsch, Touitou, Nordine, Fortus, Neumann and Krajcik, who address also the concept of energy from a perspective of transfer of knowledge and knowledge-in-use situations. The basic assumption of the authors is that the organization of learners' knowledge-networks plays an important role in successful transfer. The authors focus on questions such as how students' knowledge-networks are related to the ability to transfer knowledge to a new context and, on the other hand, to students' goal orientation. The knowledge-networks, which are in the core of the study, are constructed by the authors by using qualitative content analysis, and by identifying how science ideas are used (in a normative way) in the explanation of phenomenon. The knowledge-networks they construct on the basis of the qualitative analysis are analyzed quantitatively, to find the coherence of the networks. As a measure of coherence, the authors have chosen to use the connectedness of the networks. In addition to coherence, they also pay attention to the degree of nodes (knowledge items) as an overall measure. By using the network approach, the authors show that the students who had more coherently organized knowledge-networks also perform better on knowledge-in-use transfer tasks.

The study "Measuring Characteristics of Explanations with Element Maps" by Wagner, Kok and Priemer addresses the students' explanations by mapping the relations between the concepts the students use in providing explanations in the context of optics. By using network-based analysis, they address the question: what are the structural characteristics of good explanations? The approach designed by the authors is to construct an element map, which first lays out the lexical level of concepts and then a level, which contains semantic information. By using such approach, the authors show that experts construct more extensive explanations than novices do, but with parsimonious set of key elements. The methodological innovation presented in this study is the element map, which operationalizes the quality of the elementary structure of explanations, and makes these difficult to detect key features visualizable and measurable.

The lexical structure and lexicons are also discussed in a study "Pre-Service Teachers' Declarative Knowledge of Wave-Particle Dualism of Electrons and Photons: Finding Lexicons by Using Network Analysis" by Nousiainen and Koponen. In that study, the authors construct a lexical network of terms the students use in their written explanations of how electrons and photons behave in a double-slit experiment. The networks are then used to examine how different terms referring to particles, waves, dualism etc., appear, in relation to the terms electron and photon: on this basis, lexical profiles of terms electrons and photons are constructed. The results show that students have very different lexical profiles, differing even in the degree of providing only limited shared lexicons for basis of communication.

The concepts of electricity and magnetism from the viewpoint of conceptual change are discussed in an article "Concept Mapping in Magnetism and Electrostatics: Core Concepts and Development over Time" by Thurn, Hänger and Kokkonen. By using the concept maps, the authors have examined the changes in students' knowledge structures. As quantitative measures to monitor the changes in the structure, they have used the betweenness and PageRank centrality. The method the authors introduce is capable of demonstrating clear differences in the students' knowledge structures during the learning process. Importantly, the method can be used in practical classroom situations as a tool of evaluation.

Finally, in the set of six articles focusing on concept learning, the study "How Concept Maps with and without a List of Concepts Differ: The Case of Statistics" by Kapuza, a network-based method for analyzing concept maps is introduced. While concept maps have a long been a tool for knowledge structure assessment, their analysis has been based usually only on local counting of links. This study compares two kinds of implementation of concept maps: one with a given list of concepts and one without the list. In the study, both types of concept maps made by students were evaluated in two different ways, by using traditional scoring indicators and indicators from the network analysis. The study demonstrates that the concept maps with the list of concepts are more connected, indicating a more developed knowledge structure. The study also shows how the network analysis information complements the traditional scoring methods.

Three articles in the Special Issue combine conceptual aspects of learning with some other relevant aspects of learning. Such studies demonstrate very clearly the advantages of networks approaches in their ability to correlate multiple viewpoints.

The study "Forma Mentis Networks Reconstruct How Italian High Schoolers and International STEM Experts Perceive Teachers, Students, Scientists, and School" by Stella explores the students' mindsets related to STEM subjects and compares them to the experts' mindsets. The study presents a novel approach, where students' mindsets (forma mentis) are represented as networks, which contain information of the sentiments (forma mentis network). Such a network can be seen as an example of a feature-based network, where links not only denote an existing connection, but also contain information of the type of the connection. In their approach, the authors make use of, not only complex network methodology, but also psycholinguistic methods to uncover the sentiments related to different STEM related items. In the study, Stella pays attention to patterns that are related to the anxiety of the students, thus being able to relate the anxiety of the students to examinations, rather than to the inherent difficulty of the STEM subjects themselves. This is an important finding, and it shows the power of network approaches to reveal relevant connections that are difficult to access for traditional studies. Being aware of the complex and intertwined sets of the sentiments is relevant information for educators in designing learning environments and situations which can relieve and ameliorate the anxiety of students and, thus, improve the learning outcomes and make the learning of STEM subjects motivating and satisfying experience.

In the article "Between Social and Semantic Networks: A Case Study on Classroom Complexity" Rodrigues and Pietrocola approach the complex problem of how sociodynamics affect knowledge structures and the other way around. In their approach, they combine the network approach utilizing social structure analysis and knowledge structure analysis and correlate the results of this double-targeted analysis. The theoretical background of the work is, on the one hand, anchored in Social Network Analyses and, on the other hand, in Social Representation Theory. The findings of the study show that the close relations are found between social ties' and a consensus formed on intra-school representational objects, but there is a weak dependence between consensus on extra-school representational objects. This study exemplifies how it is possible to map out relationships and the relationships of relations by using networks, which can reveal indirect and intertwined dependencies, which are of importance not only for analysis of data, but also for novel ways to conceptualize the phenomenon.

A third study which combines different types of network analyses is "Student Participation in Online Content-Related Discussion and Its Relation to Students' Background Knowledge", where Turkkila and Lommi examined how students' activity in an asynchronous web-based discussion correlates with their background knowledge about the topic. To explore how these aspects are correlated, a detailed analysis of content of discussion is first carried out by using qualitative epistemic content analysis, and analyzing the role of students in turn-taking in the discussions. The roles in turn-taking where analyzed by using a network approach to detect the functional roles. The students' background knowledge was analyzed using Katz and degree centralities to students' association chains of certain physics history topics. As a result, there was a measure for each students' overall association chain, and a combined overall network of all students' association chains. Somewhat unexpectedly, the detailed analysis finds very low or even non-existent correlations between activity and richness and connectedness of background knowledge. The study underlines the importance of being explicit about the type of knowledge, when background knowledge is assessed, and specifically to network measures, how that background knowledge is characterized.

The network analysis can also be used in areas of interest for science education, where instead of concepts and conceptual learning some other phenomena are in focus. Among such applications, the collection of papers in this Special Issue provide three examples.

In the article "Network Analysis of Survey Data to Identify Non-Homogeneous Teacher Self-Efficacy Development in Using Formative Assessment Strategies", Bruun and Evans investigate teachers' self-efficacy in their use of formative assessment. The authors use network analysis in analyzing the relational response pattern of survey questions, to identify clusters of patterns and the internal structure of the patterns. Using the network-based methodology, the authors show that, while the data shows gains in self-efficacy in general, the patterns contain information of heterogeneous development within the (super) groups of similar teachers. This is an interesting finding and, at the same time, an illustrative example of the power of network analysis in bringing forward patterns not so evident in the data at first sight. The possibility to reveal such indirect and subtle connections is an important step towards better understanding what kinds of factors are behind the self-efficacy of the teacher in adopting new instruction methods, in this case assessment forms, and where and why they might falter and have weak self-efficacy.

Another study which addresses factors known to be importance for learning but not directly connected to learning process or conceptual structures is reported in the article "Combining Surveys and Sensors to Explore Student Behaviour" by Kontro and Génois, where the sociodynamics of students during laboratory sessions is explored. In that study, the group dynamics of introductory physics students was explored by using the SocioPatterns platform, and that information was supplemented with students' background information, performance in the Mechanics Baseline Test, to measure their physics knowledge, and with answers to the Colorado Learning Attitudes Test about Science Survey to measure their attitudes. Through the network analysis of data, the authors found both demographically homogeneous and heterogeneous groups that are stable. The results show how a network analysis based on SocioPatterns supplemented with surveys thus provides an opportunity to look into the dynamics of students' social networks.

The third study in this set of examples, "Scanning Signatures: a graph theoretical model to represent visual scanning processes and a proof of concept study in biology education" by Moreno-Esteva, Kervinen, Hannula and Uitto, shows how networks may also have applications in research settings, which explore students' attention and focus in learning situations. The study reports how eye-movement tracking can be analyzed by using networks. The analysis reveals how people with different levels of expertise pay attention on certain features of birds: apparently those features are significant for the function of body-parts of the birds, and give information of the birds' adaptation to their habitats. This is an interesting observation, given that, in taxonomization, functionality is assumed to be of key importance. The network analysis also makes possible the temporal analysis of eye-movements, which could lead to interesting information of the relation of conceptual disciplinary knowledge and the perceptual process of observation.

In summary, the articles in this Special Issue cover a broad range of topics, varying from studies concerned with single students' conceptual learning, to studies where a sociosemantic approach is taken, embracing the sociodynamics, as well as the cognitive dynamics, of learning. The phenomena studied are, of course, the core topics in science education, and have been in the foreground for decades, but only recently, network-based approaches have been adopted to tackle these complex problems. The articles published in this Special Issue demonstrate that, by using complex networks, in-depth analyses and new ways to carry out integrative research approaches become possible. We hope that the collection of articles presented in this Special Issue encourages researchers to explore the potential of these new methods, not to replace the existing good methods, but to augment and complement them and, also, to find fresh ways to conceptualize the phenomena of learning and teaching and, perhaps, become aware of new interesting (complex) phenomena.

Conflicts of Interest: The authors declare no conflict of interest.

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